Berkeley-ISICLES (BISICLES): High Performance Adaptive Algorithms For Ice Sheet Modeling

Dan Martin

Lawrence Berkeley National Laboratory

June 22, 2011

U.S. DEPARTMENT OF ENERGY | Office of Science

BISICLES

BERKELEY LAB

Los Alamos NATIONAL LABORATORY EST. 1943

University of BRISTOL

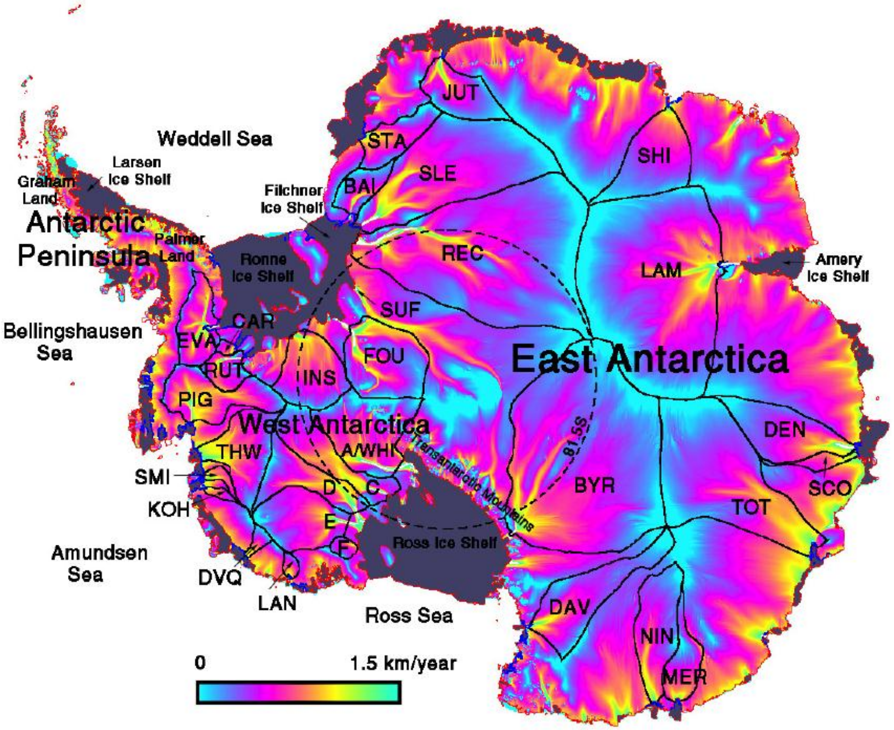
BISICLES - Goal

Goal: Build a parallel, adaptive ice-sheet model

- Localized regions where high resolution needed to accurately resolve ice-sheet dynamics (500 m or better at grounding lines)
- Large regions where such high resolution is unnecessary (e.g. East Antarctica)
- Problem is well-suited for adaptive mesh refinement (AMR)
- Want good parallel efficiency
- Need good solver performance

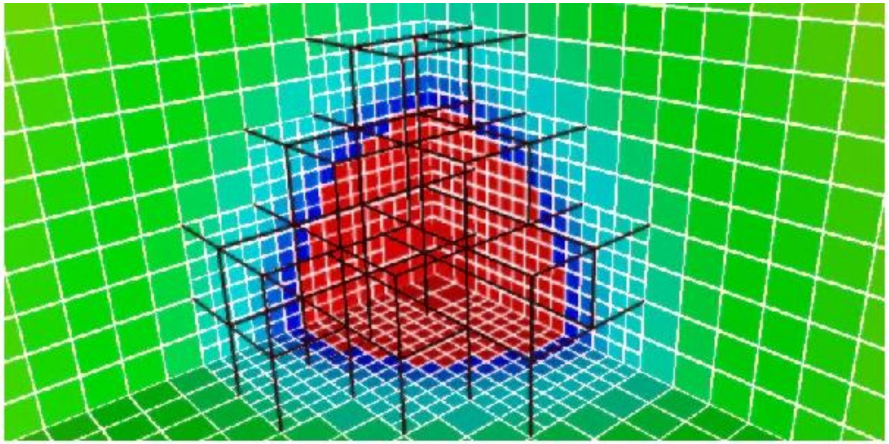
Much higher resolution (1 km versus 5 km) required in regions of high velocity (yellow → green).

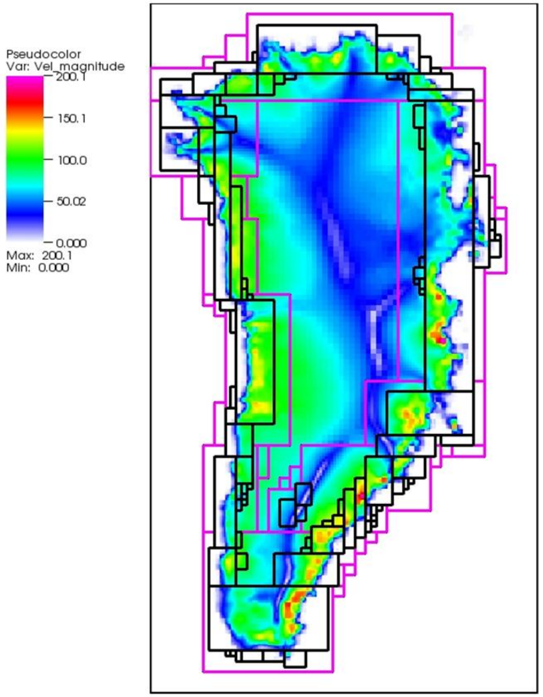
[Rignot & Thomas, 2002]



BISICLES – Approaches

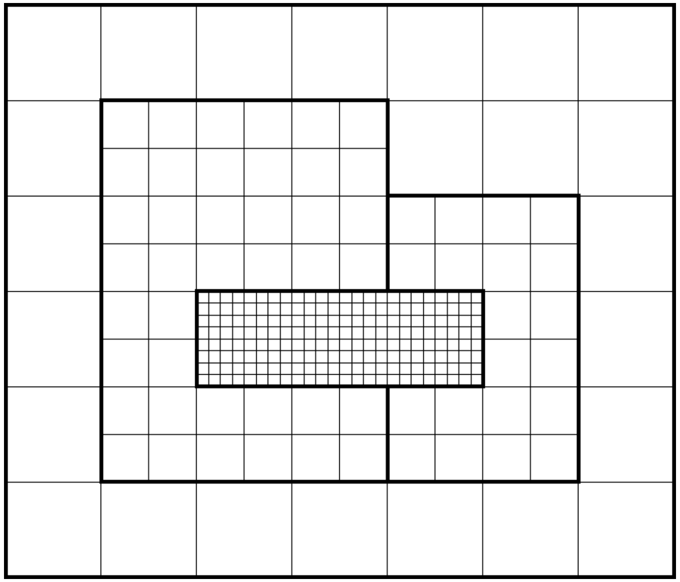
- Develop an efficient parallel implementation of Glimmer-CISM by
  - Incorporating structured-grid AMR using the Chombo framework to increase resolution where needed
  - Exploring new discretizations and formulations where appropriate (L1L2)
  - Improving performance and convergence of linear and nonlinear solvers, and
  - Deploying auto-tuning techniques to improve performance of key computational kernels.

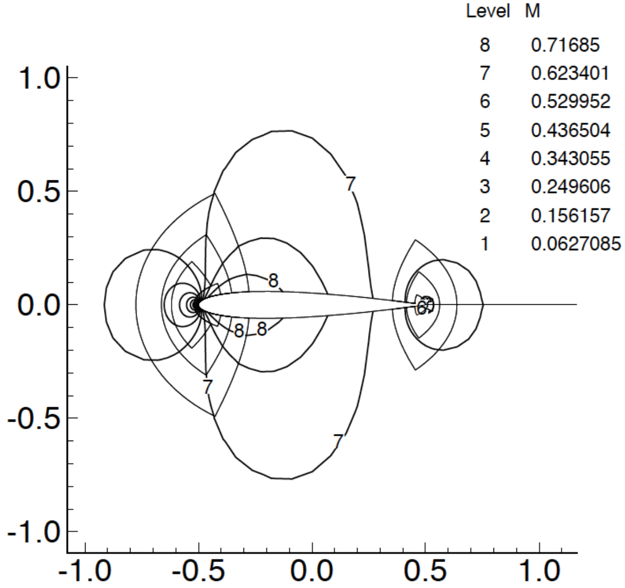


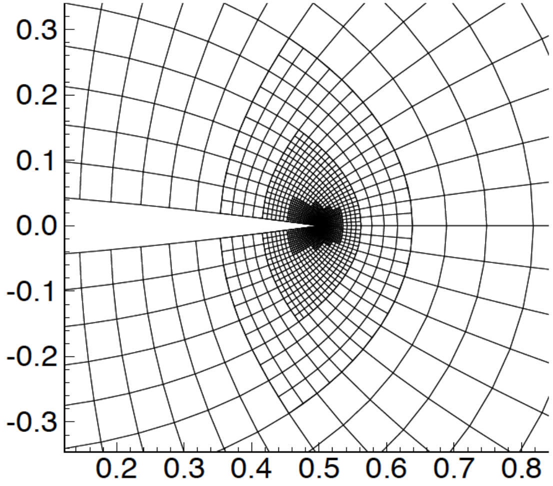


Block-Structured Local Refinement

- Refined regions are organized into rectangular patches.







- *Algorithmic advantages:*
  - *Build on mature structured-grid discretization methods.*
  - *Low overhead due to irregular data structures, relative to single structured-grid algorithm.*

"L1L2" Model (Schoof and Hindmarsh, 2010).

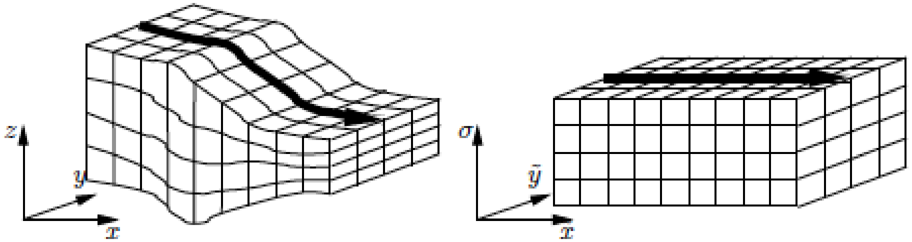
- Uses asymptotic structure of full Stokes system to construct a higher-order approximation
  - Expansion in ε -- ratio of length scales $\frac{[h]}{[x]}$
  - Computing velocity to $O(\varepsilon^2)$ only requires τ to $O(\varepsilon)$

- Computationally **much** less expensive -- enables fully 2D vertically integrated discretizations. (can reconstruct 3d)

- Similar formal accuracy to Blatter-Pattyn $O(\varepsilon^2)$
  - Recovers proper fast- and slow-sliding limits:
    - SIA $(1 \ll \lambda \leq \varepsilon^{-1/n})$ -- accurate to $O(\varepsilon^2 \lambda^{n-2})$
    - SSA $(\varepsilon \leq \lambda \leq 1)$ - accurate to $O(\varepsilon^2)$

Discretizations

- Baseline model is the one used in Glimmer-CISM:
  - Logically-rectangular grid, obtained from a time-dependent uniform mapping.
  - 2D equation for ice thickness, coupled with 2D steady elliptic equation for the horizontal velocity components. The vertical velocity is obtained from the assumption of incompressibility.
  - Advection-diffusion equation for temperature.



$$\frac{\partial H}{\partial t} = b - \nabla \cdot H\bar{\mathbf{u}}$$

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\nabla^2 T - \mathbf{u}\cdot\nabla T + \frac{\Phi}{\rho c} - w\frac{\partial T}{\partial z}$$

- Use of Finite-volume discretizations (vs. Finite-difference discretizations) simplifies implementation of local refinement.
- Software implementation based on constructing and extending existing solvers using the Chombo libraries.

Interface with Glimmer-CISM

- Glimmer-CISM has coupler to CESM, additional physics
  - Well-documented and widely accepted
- Our approach – couple to Glimmer-CISM code as an alternate "dynamical core"
  - Allows leveraging existing Glimmer-CISM capabilities
  - Use the same coupler to CESM
  - BISICLES code sets up within Glimmer-CISM and maintains its own storage, etc.
  - Communicates through defined interface layer
  - Instant access to a wide variety of test problems
  - Interface development almost complete
  - Part of larger alternative "dycore" discussion for Glimmer-CISM

Recent Progress (Since January LIWG)

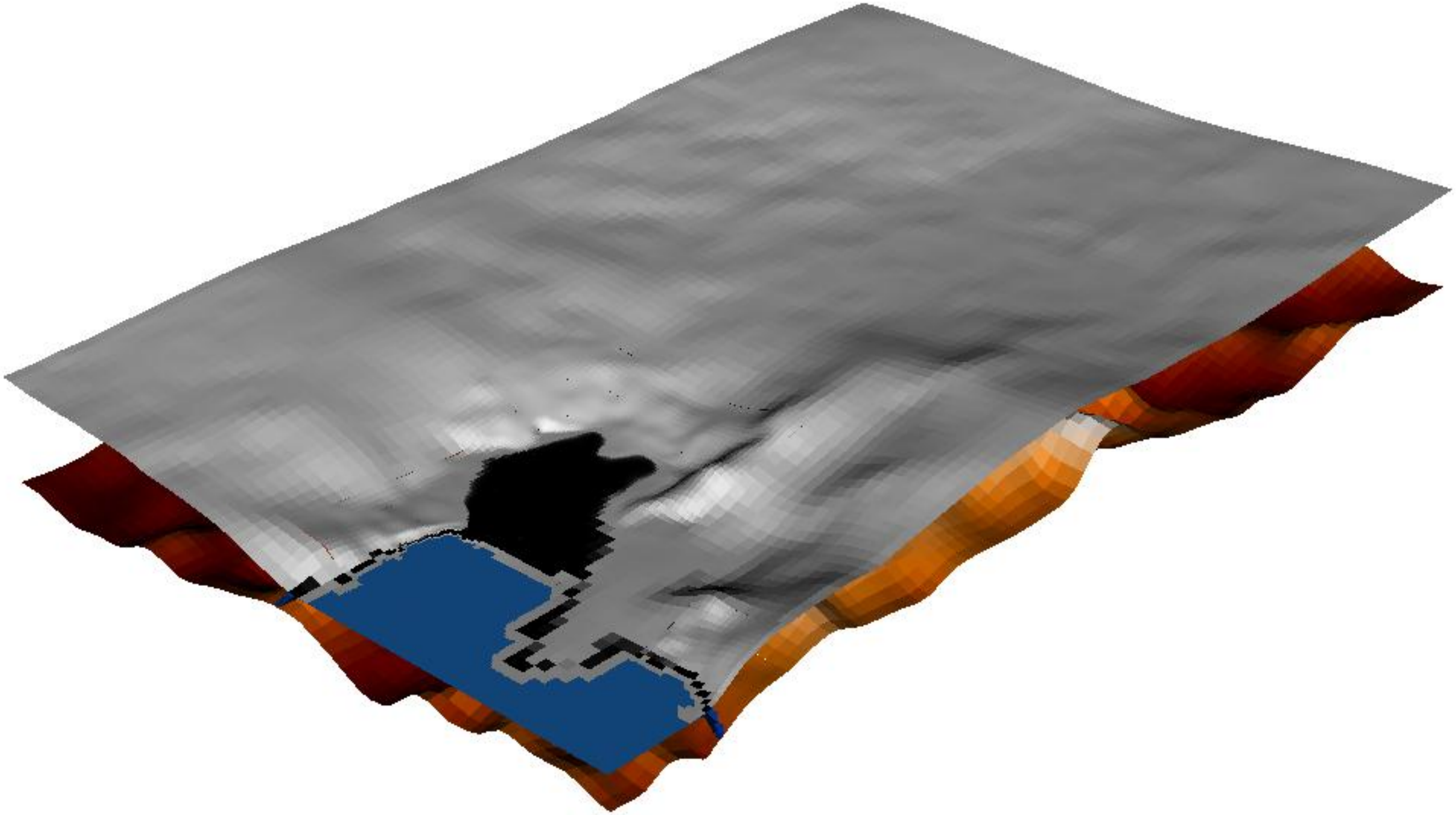
- Added temperature solver
  - Horizontal and vertical advection, vertical diffusion
  - Currently testing

- Linear and nonlinear solver improvements (improved robustness)
- Improvements to Glimmer-CISM/BISICLES dycore interface and design
- Some software redesign
- Basic calving model

BISICLES Results – Pine Island Glacier

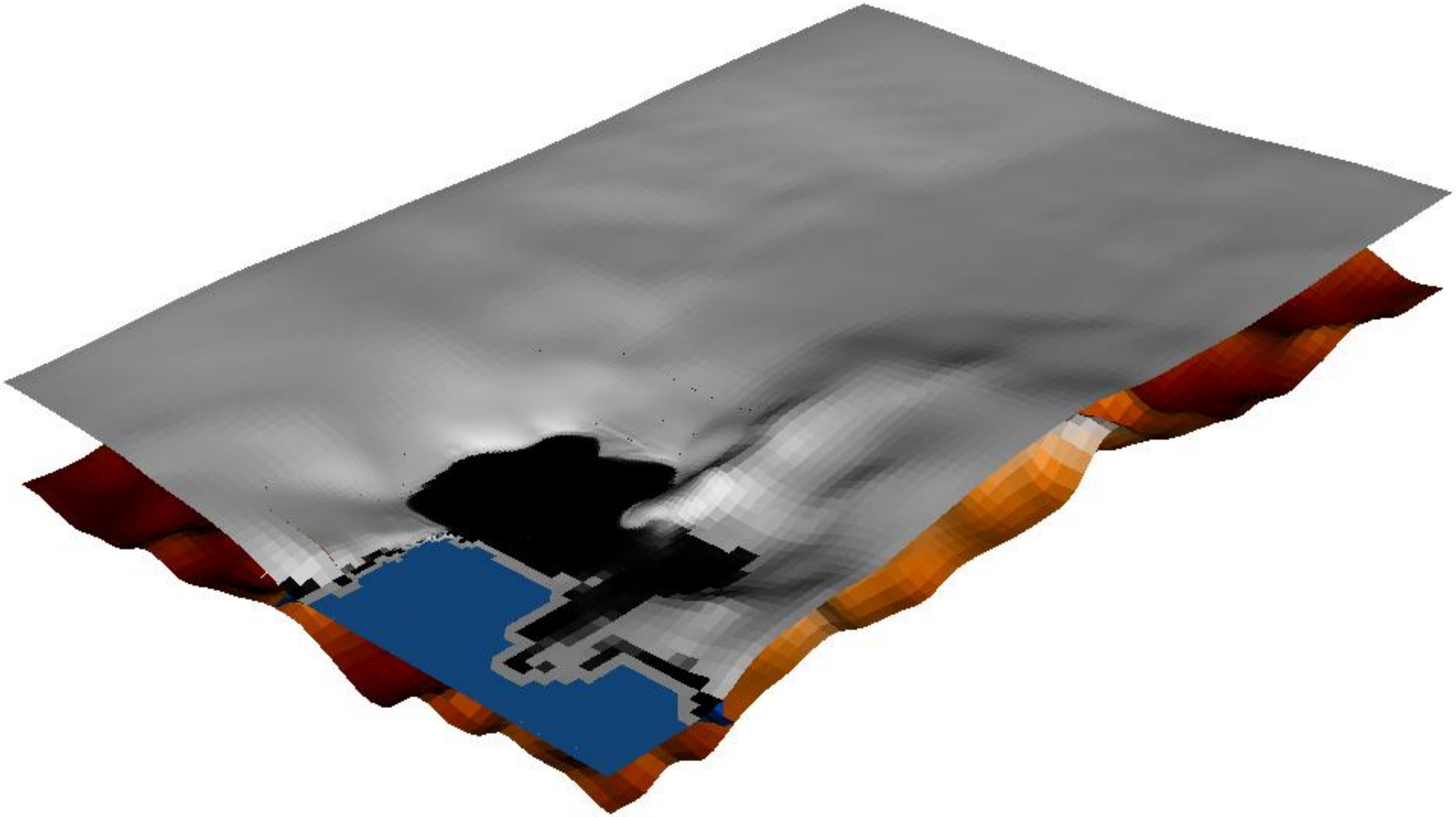
- Poster by Cornford, et al
- PIG configuration from LeBrocq:
  - Bathymetry: combined Timmerman (2010), Jenkins (2010), Nitsche (2007)
  - AGASEA thickness
  - Isothermal ice, A=4.0× $10^{-17}\ Pa^{-\frac{1}{3}} m^{-1/3} a$
  - Basal friction chosen to roughly agree with Joughin (2010) velocities
- Specify melt rate under shelf:
  - $$M_s = \begin{cases} 0 & H < 50m \\ \frac{1}{9}(H-50) & 50 \le H \le 500m \\ 50 & H > 500\,m \end{cases} \quad \text{m/a}$$
- Constant surface flux = 0.3 m/a
- Evolve problem – refined meshes follow the grounding line.
- Calving model and marine boundary condition at calving front

Pine Island, cont



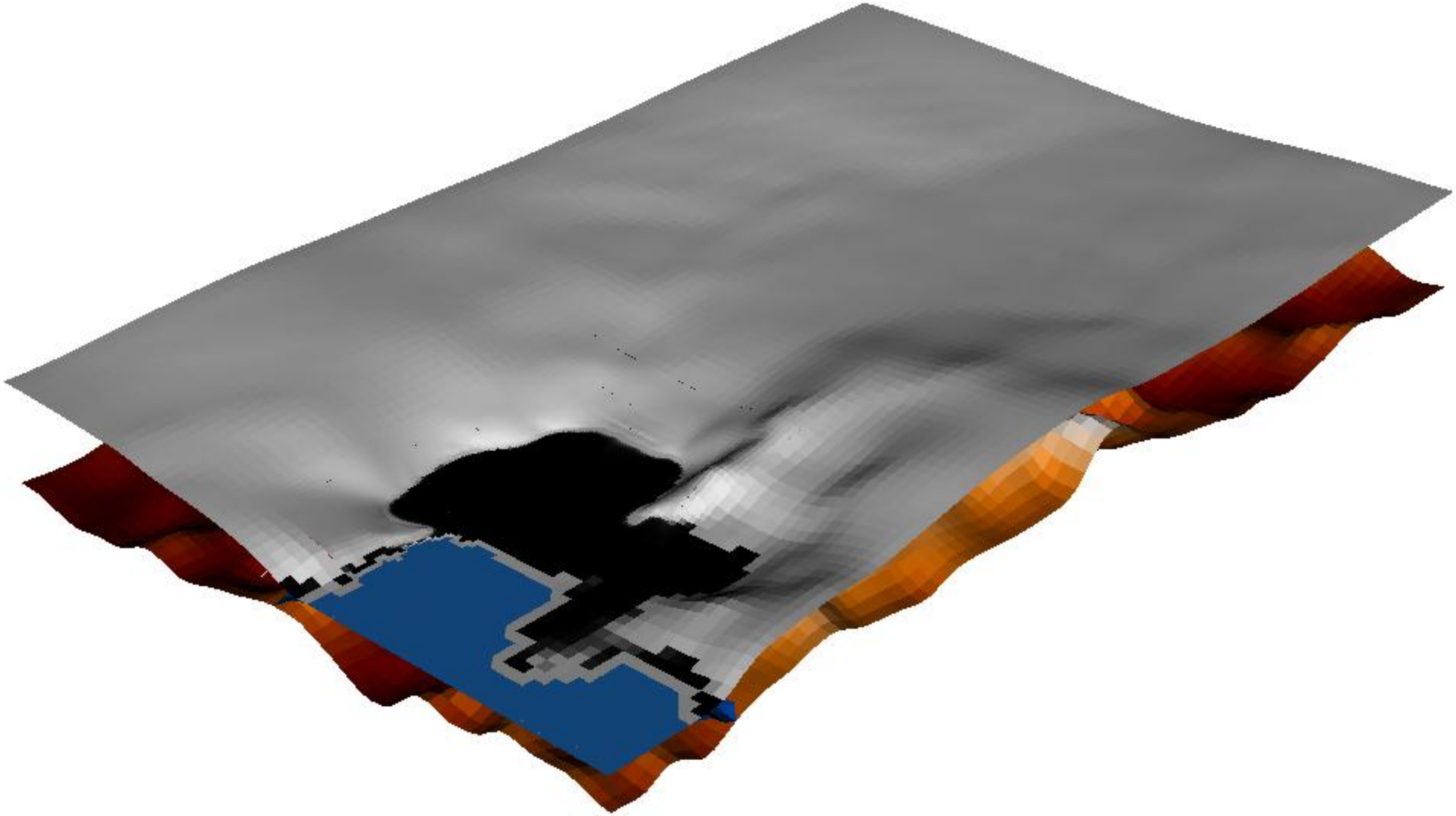
Ice shelf, grounding line, t = 0

Pine Island, cont



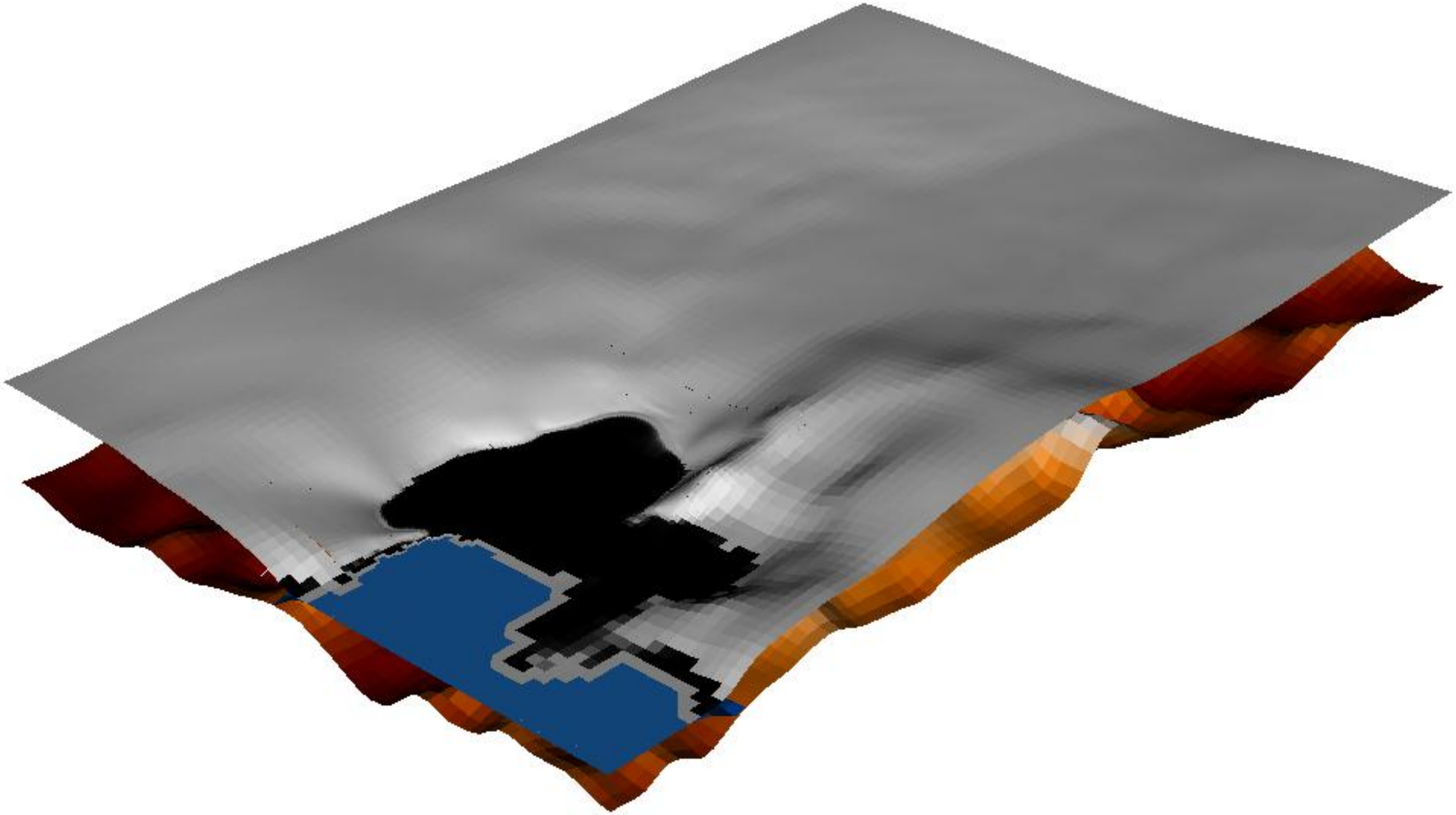
Ice shelf, grounding line, t = 7.75yr

Pine Island, cont



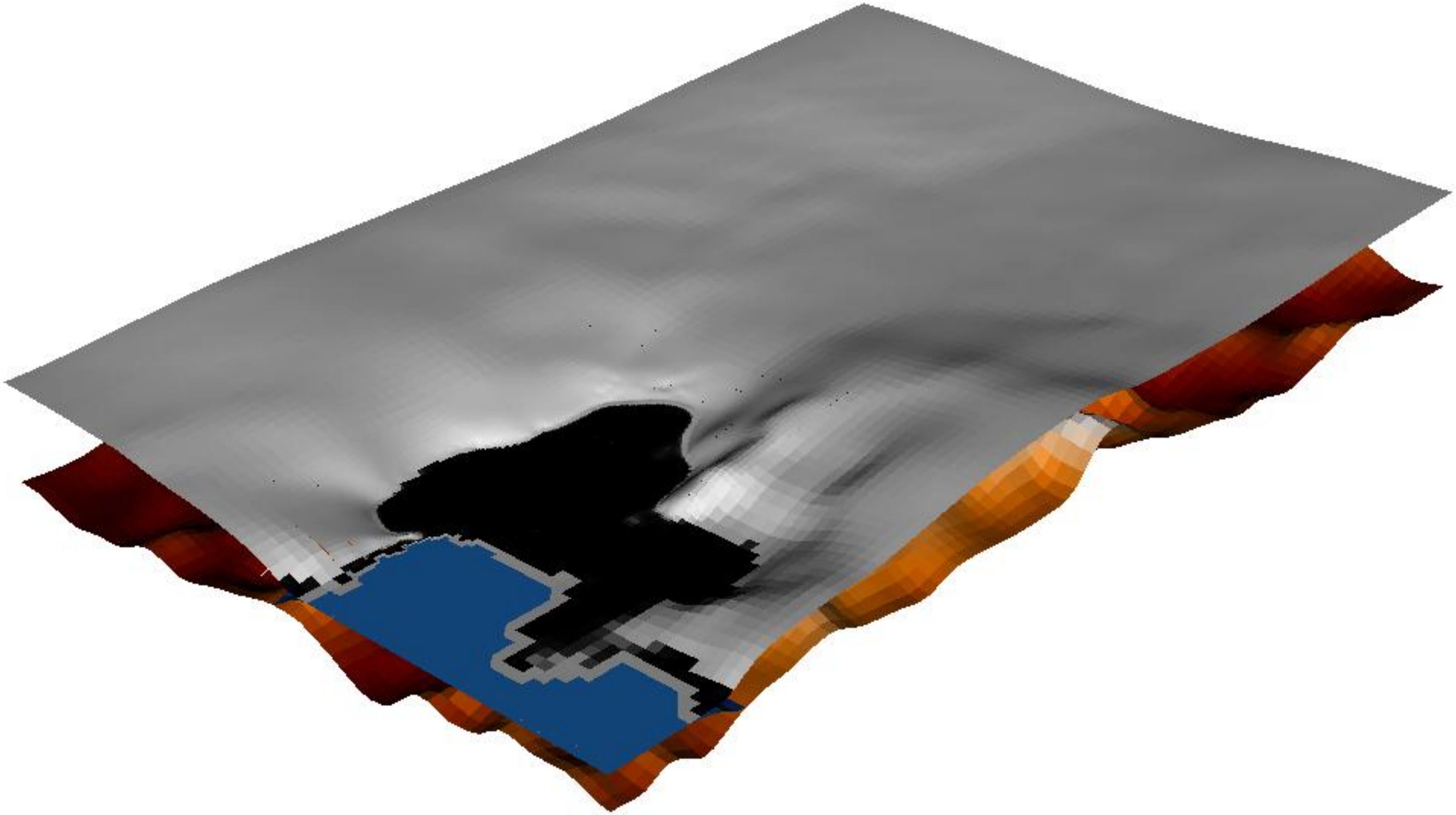
Ice shelf, grounding line, t = 15.65yr

Pine Island, cont



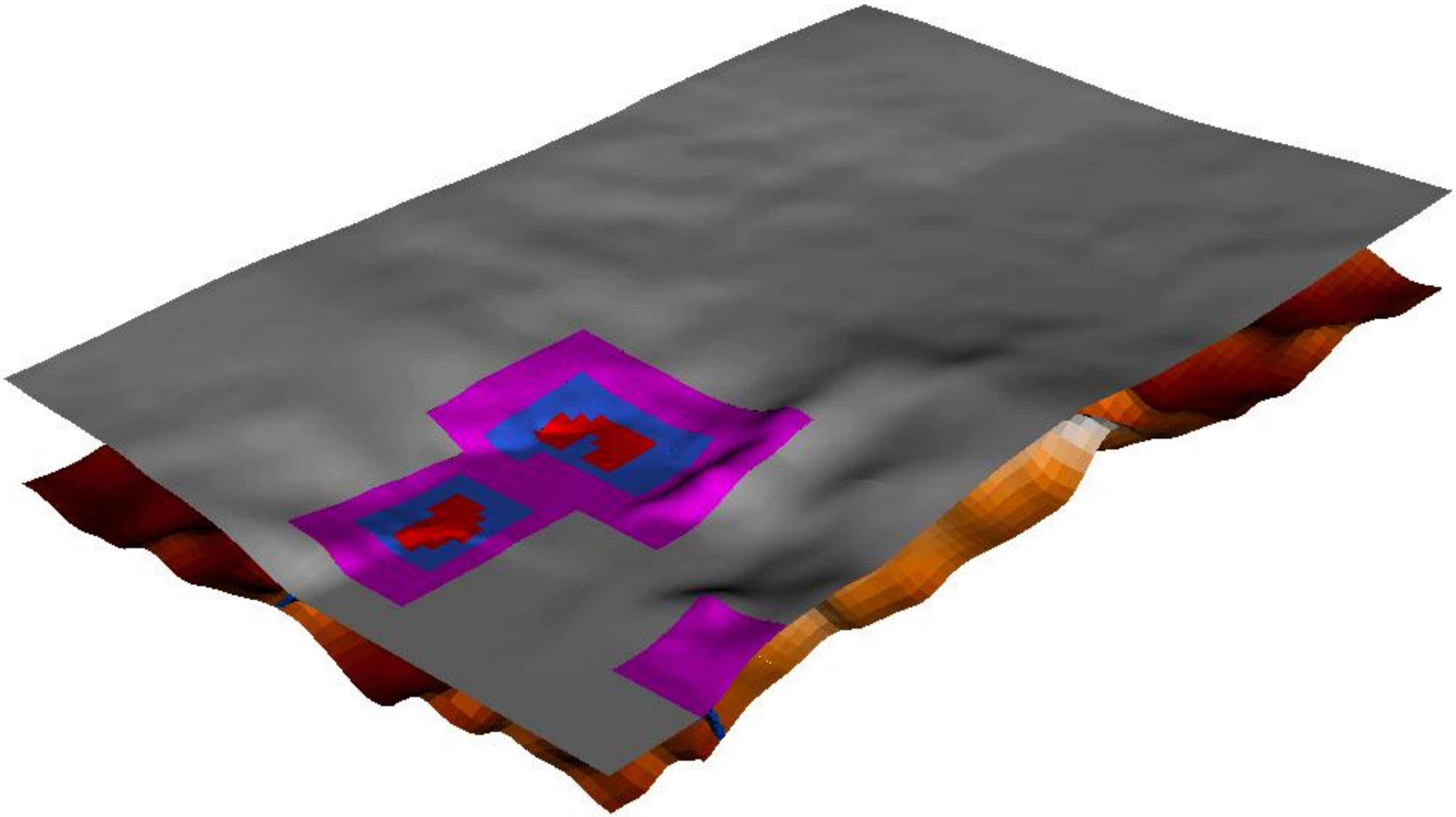
Ice shelf, grounding line, t = 23.56yr

Pine Island, cont



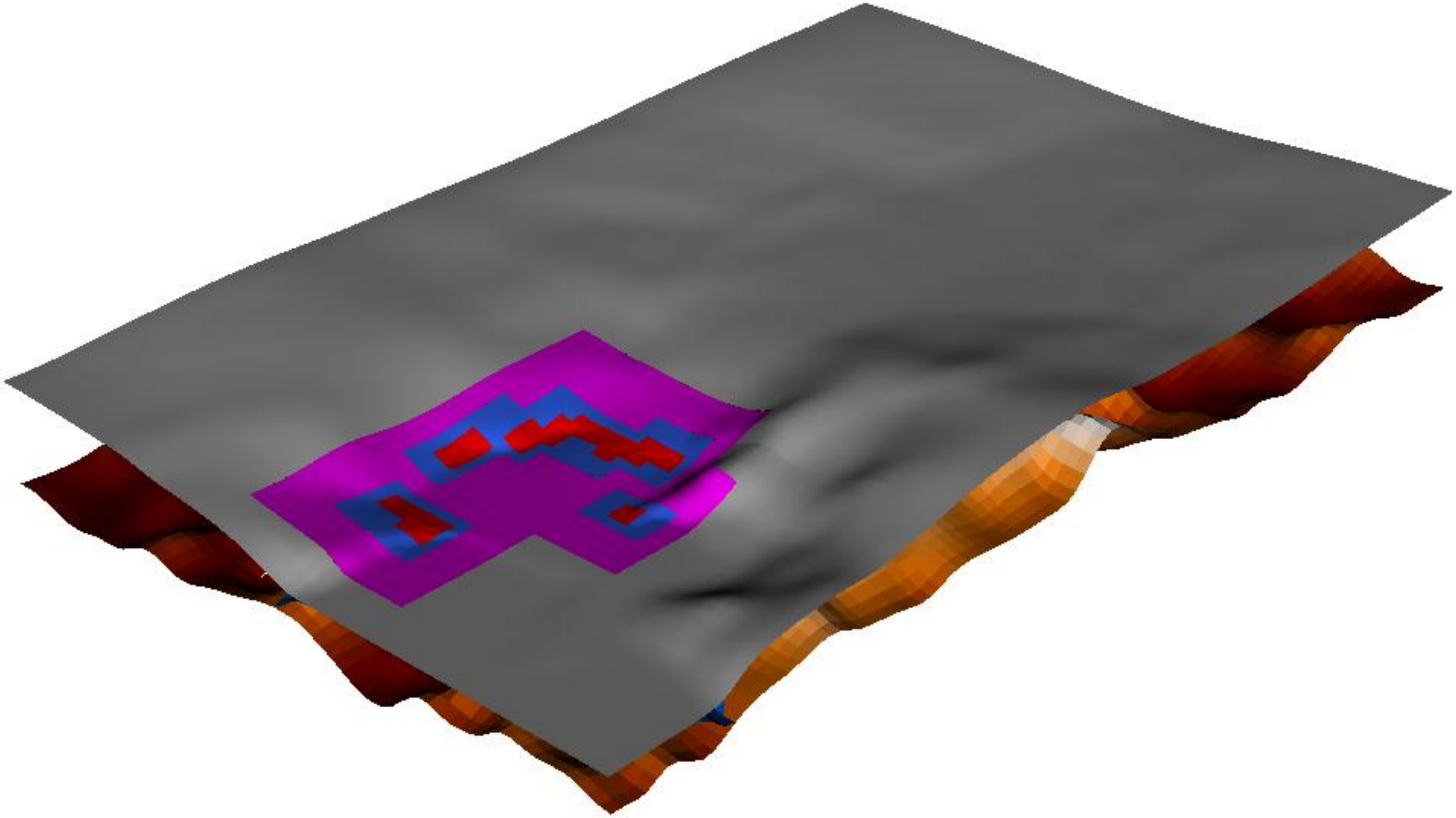
Ice shelf, grounding line, t = 31.125yr

Pine Island, cont



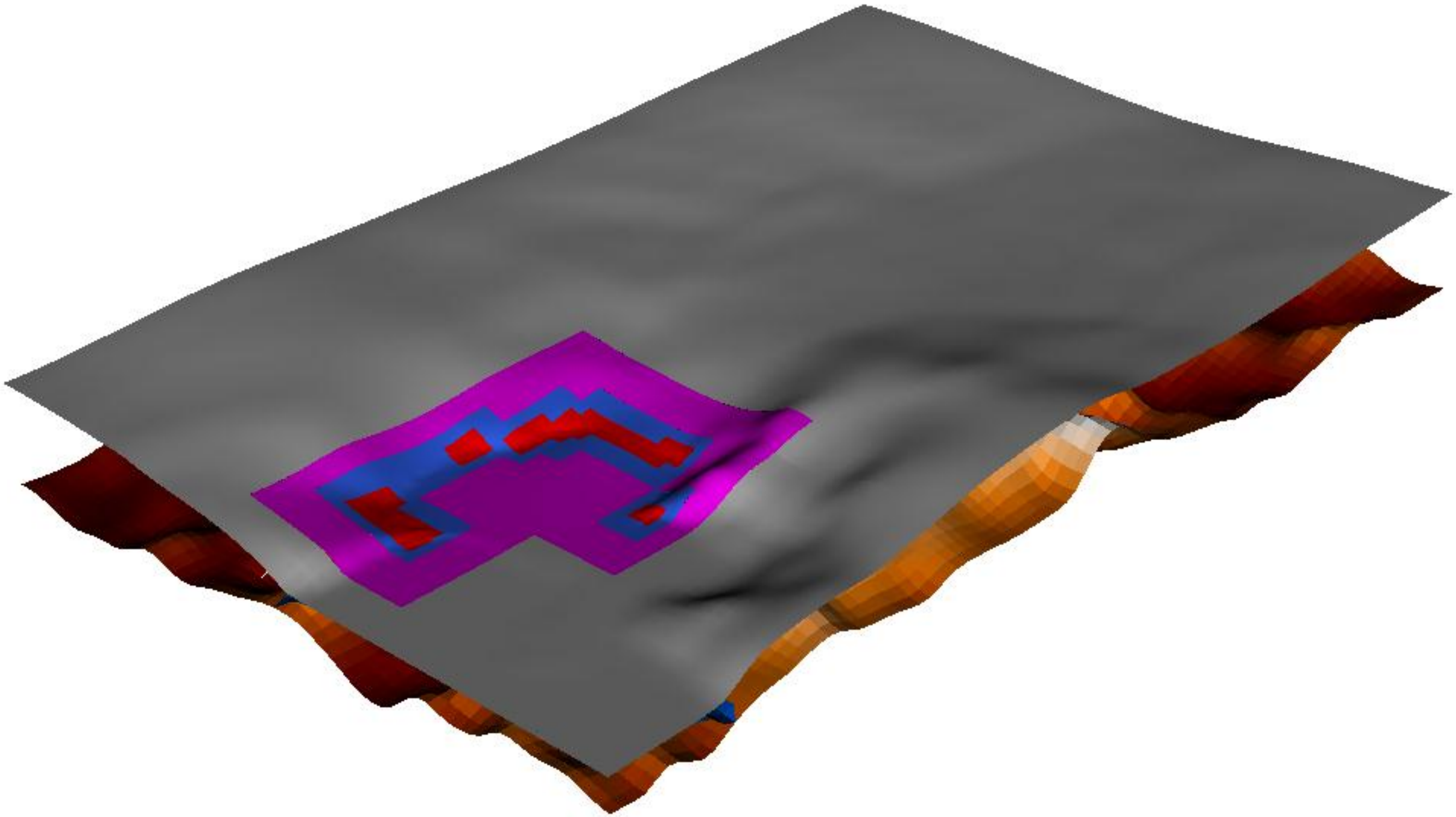
Refined mesh, t = 0

Pine Island, cont



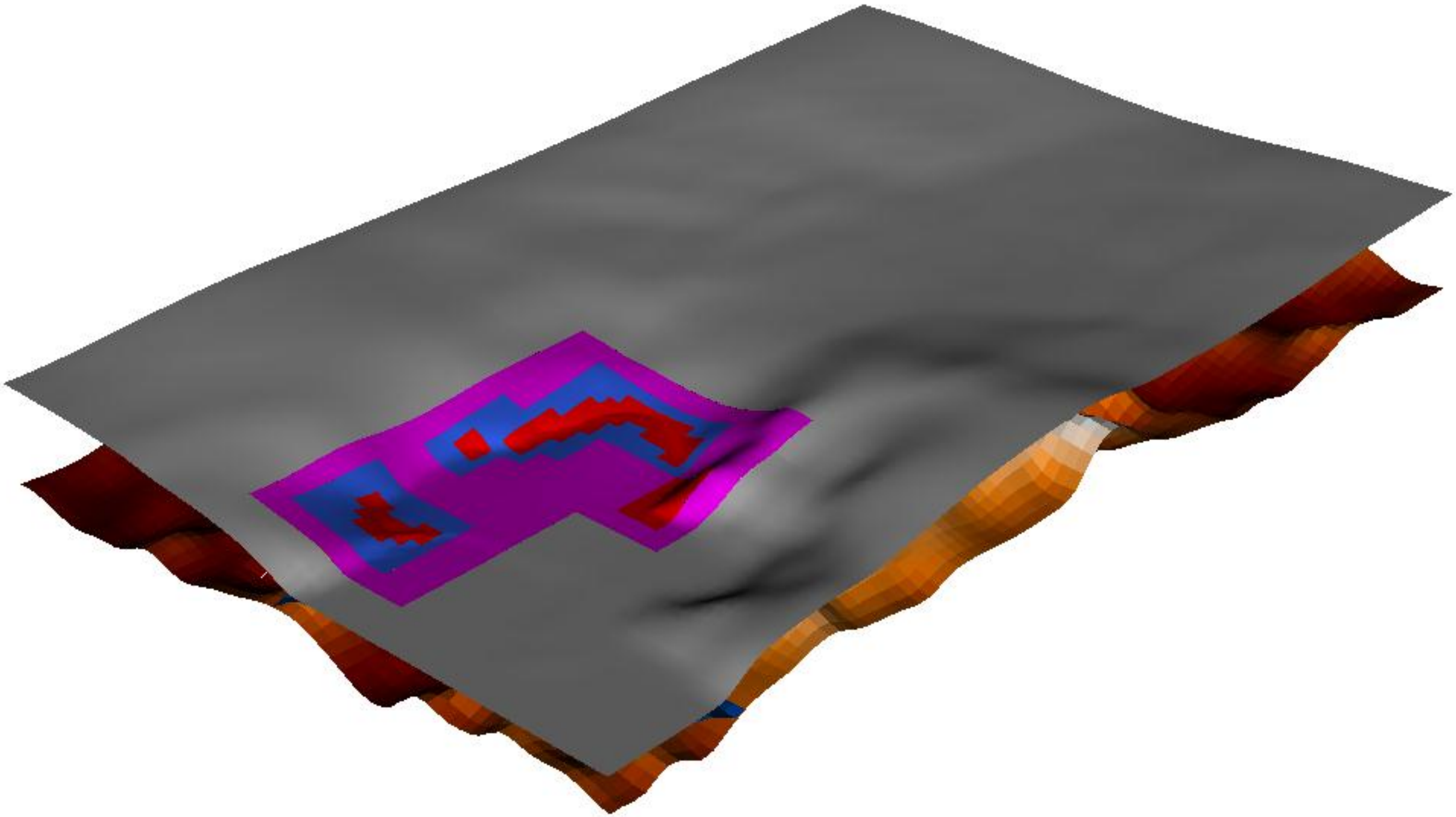
Refined mesh, t = 7.75yr

Pine Island, cont



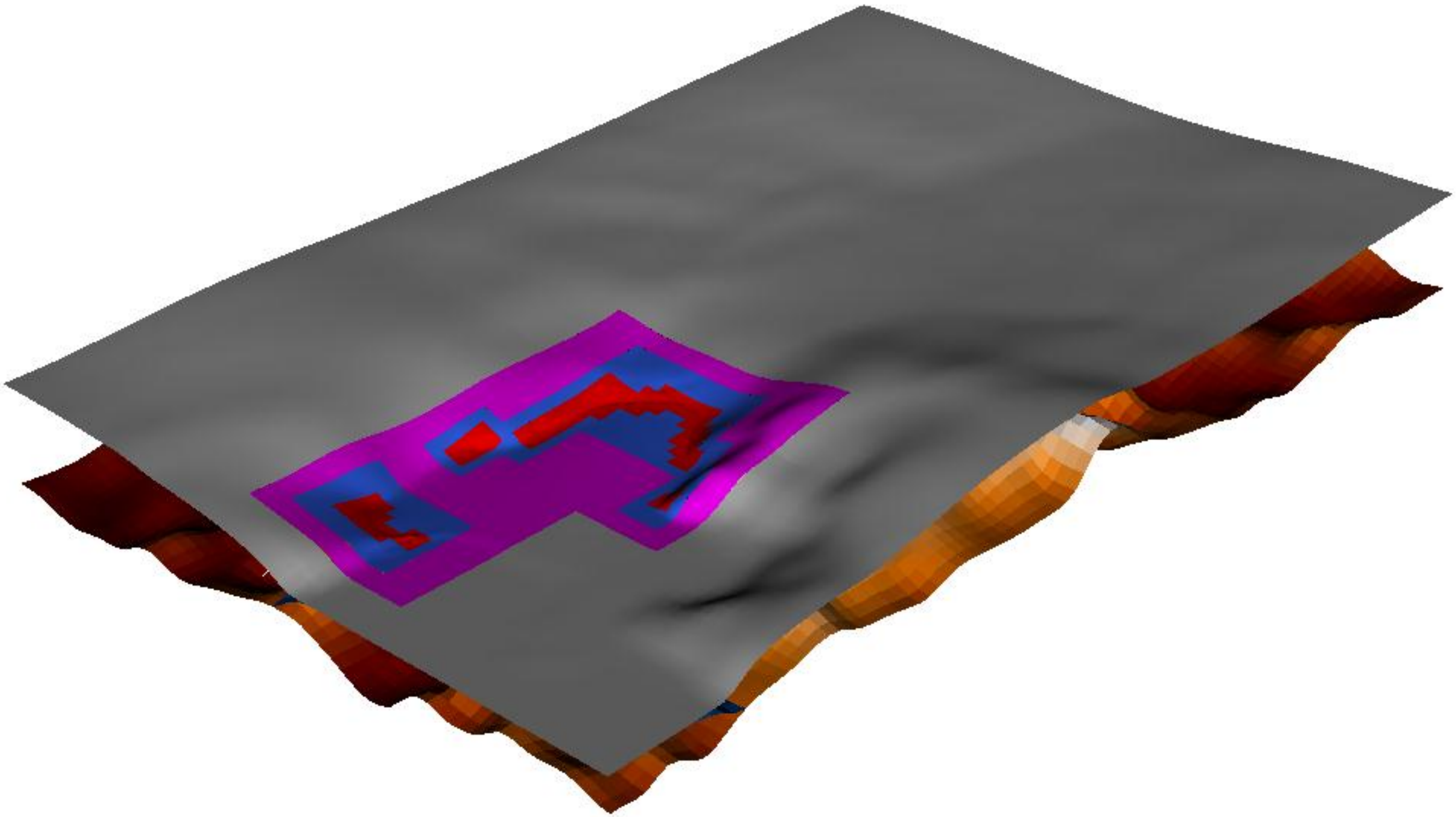
Refined mesh, t = 15.625yr

Pine Island, cont



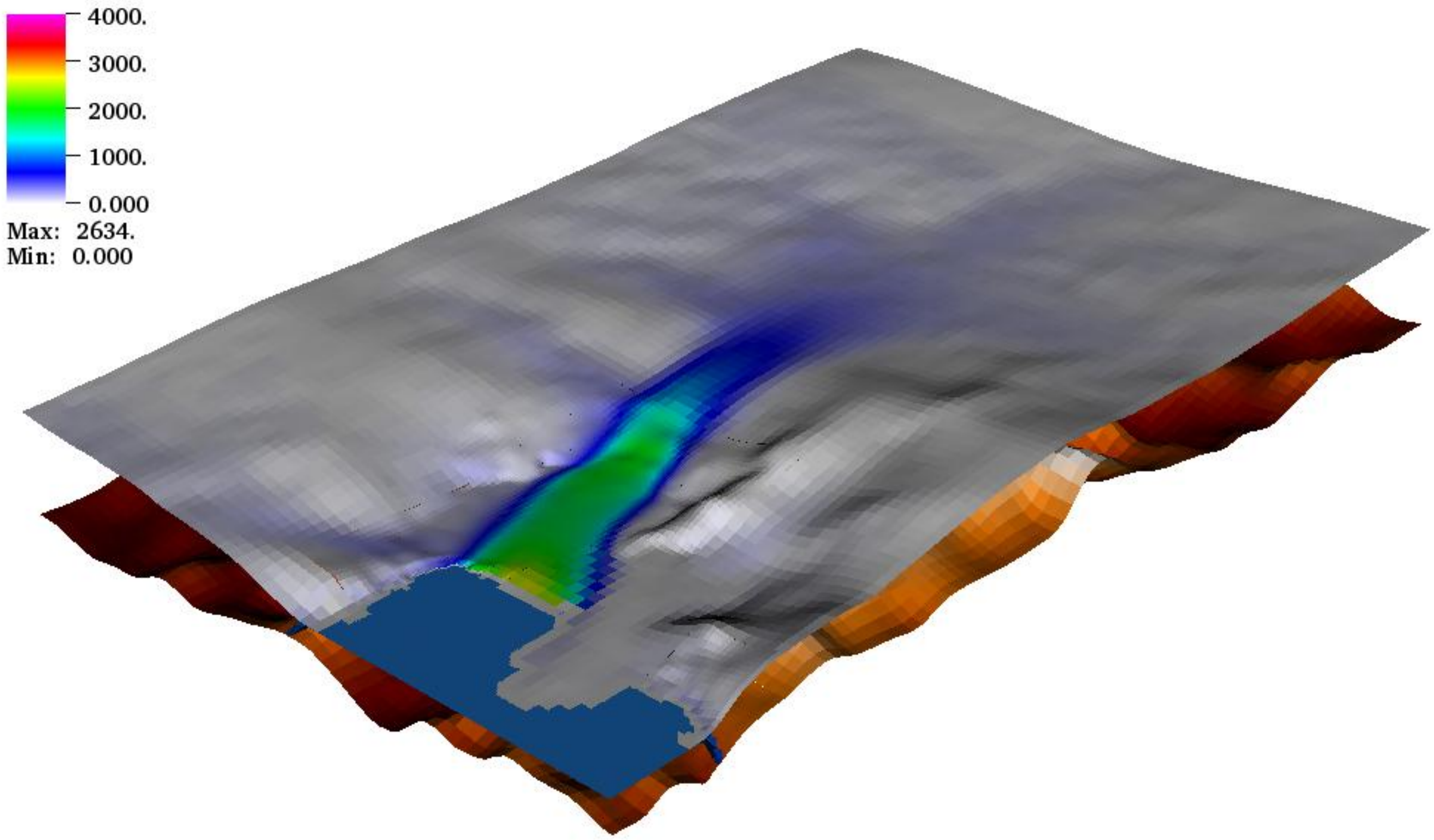
Refined mesh, t = 23.575yr

Pine Island, cont



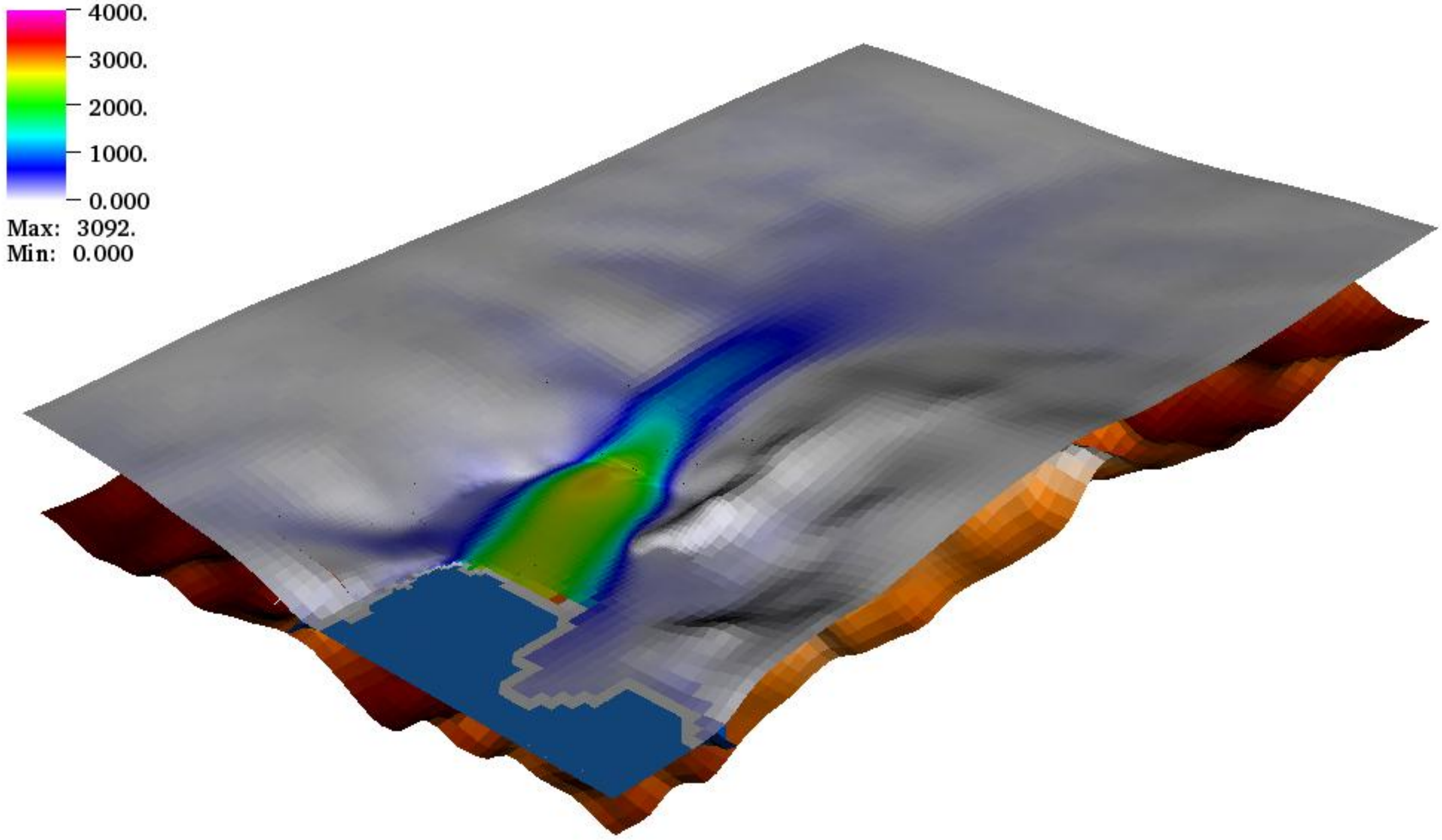
Refined mesh, t = 30.125yr

Pine Island, cont



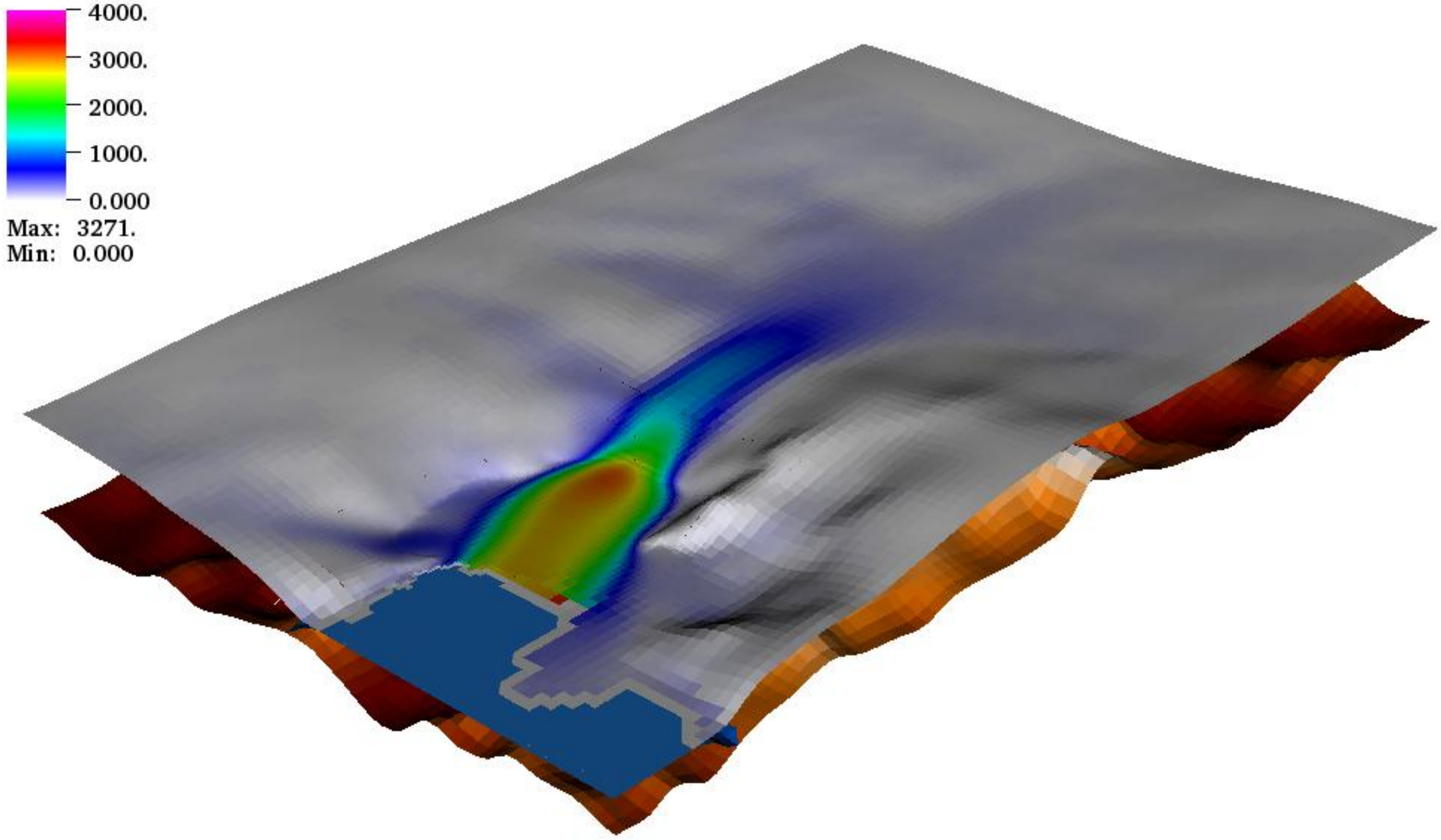
Basal ice velocity, t = 0

Pine Island, cont



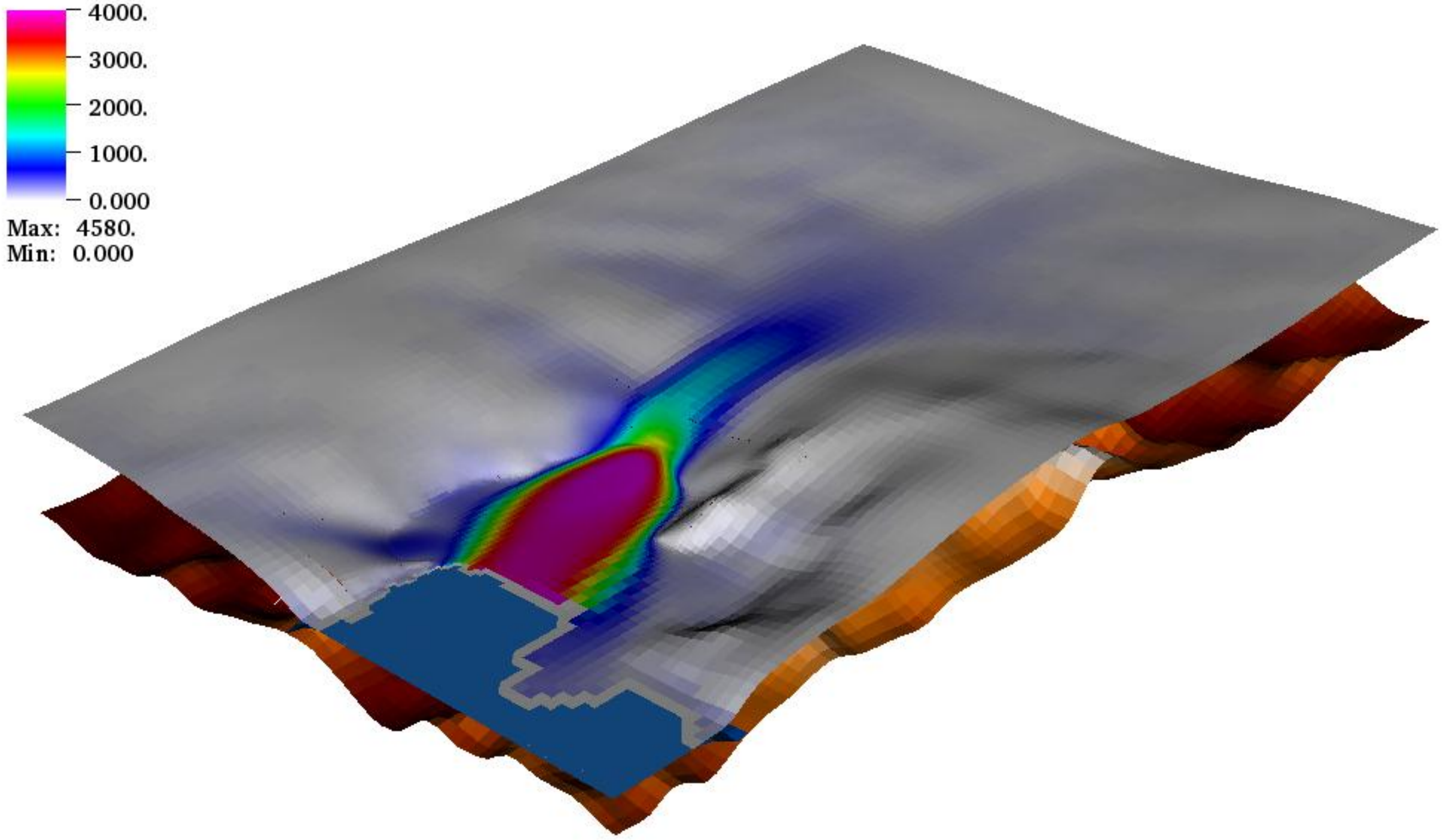
Basal ice velocity, t = 7.75

Pine Island, cont



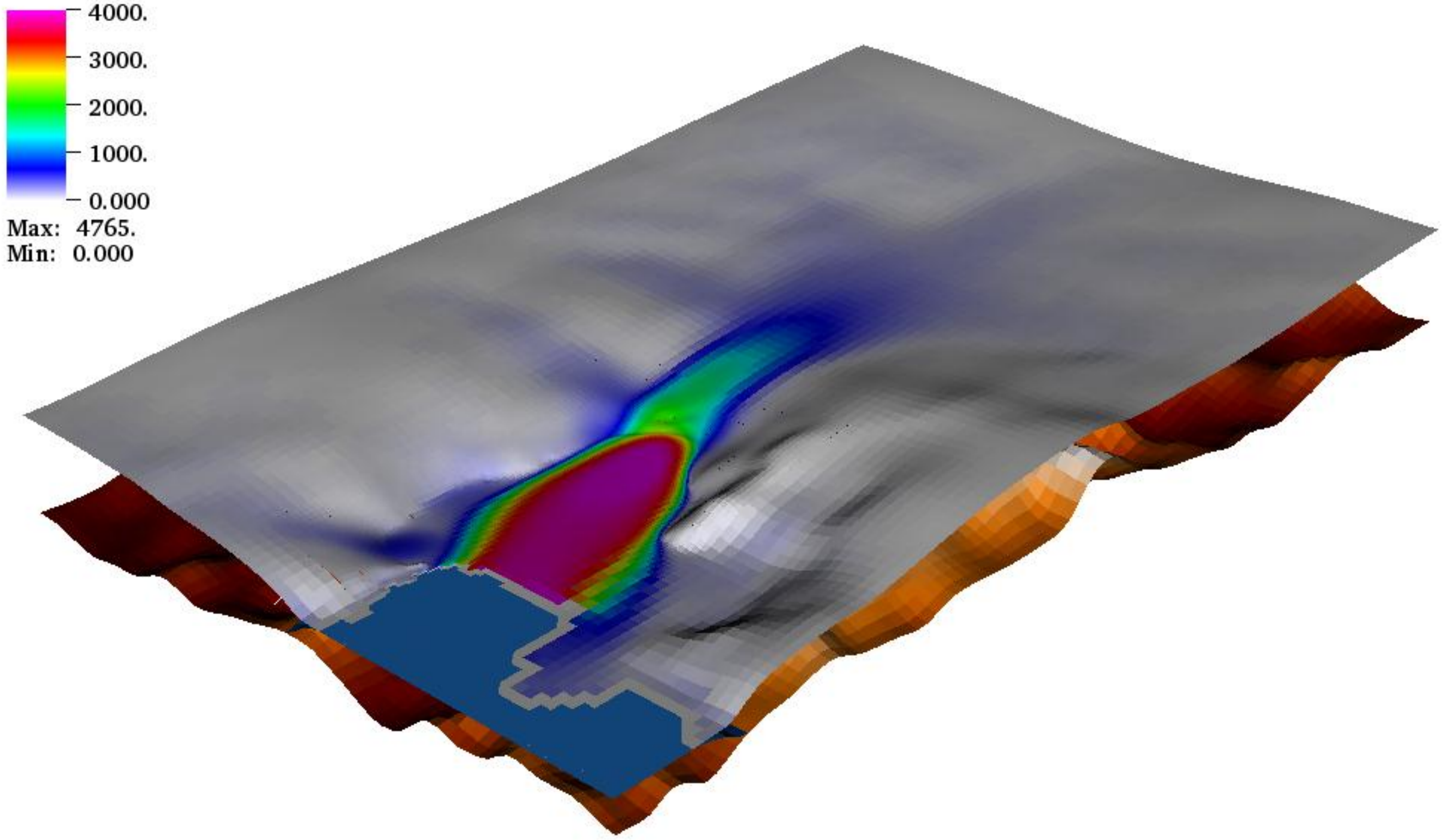
Basal ice velocity, t = 15.625

Pine Island, cont



Basal ice velocity, t = 23.375

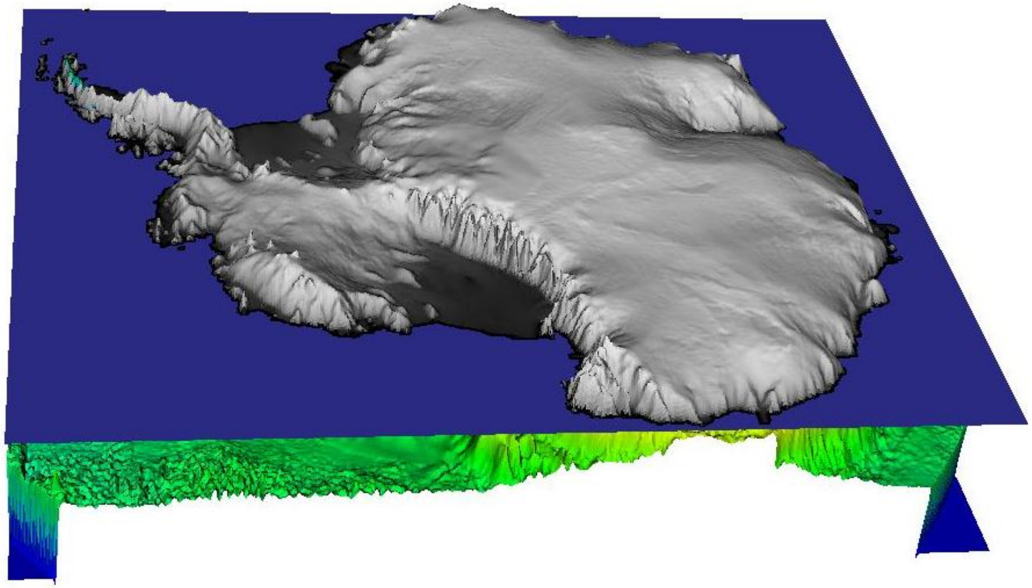
Pine Island, cont

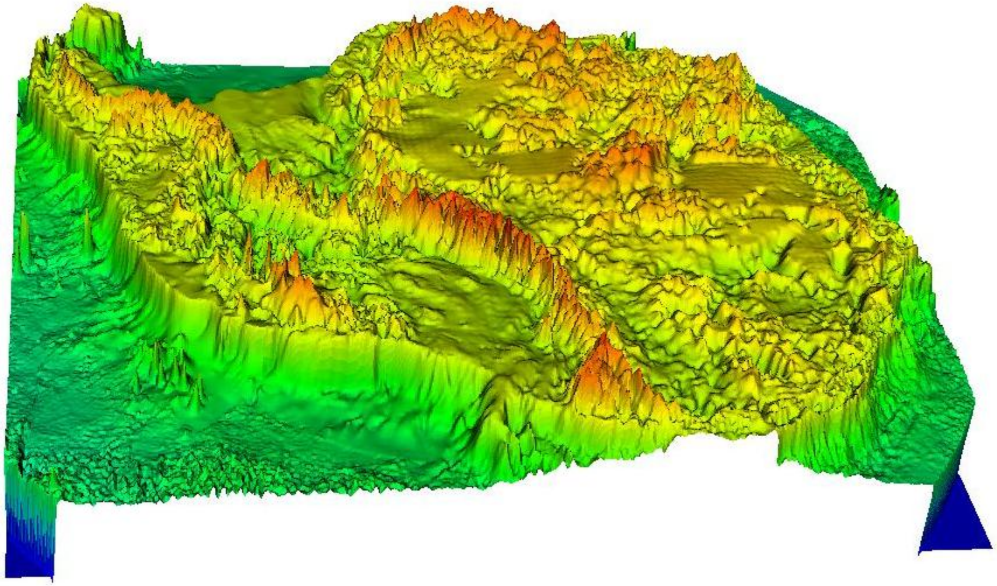


Basal ice velocity, t = 31.125

Antarctica

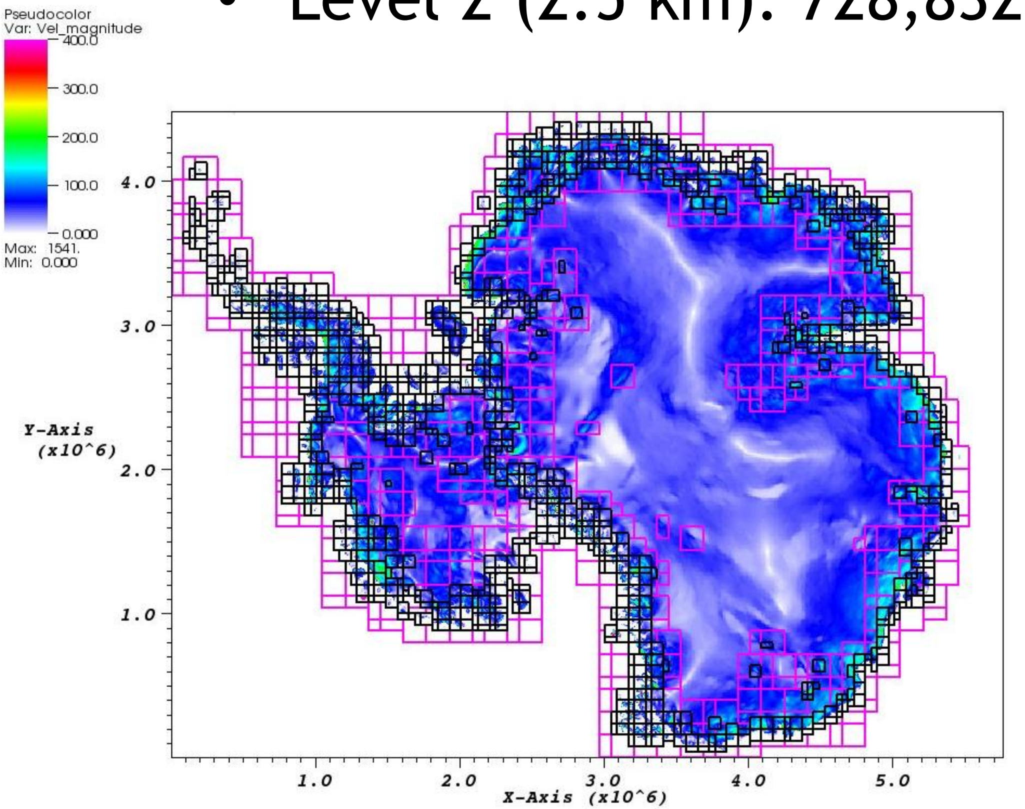
Uses new "model-friendly" problem setup
(Le Brocq, Payne, Vieli (2010))

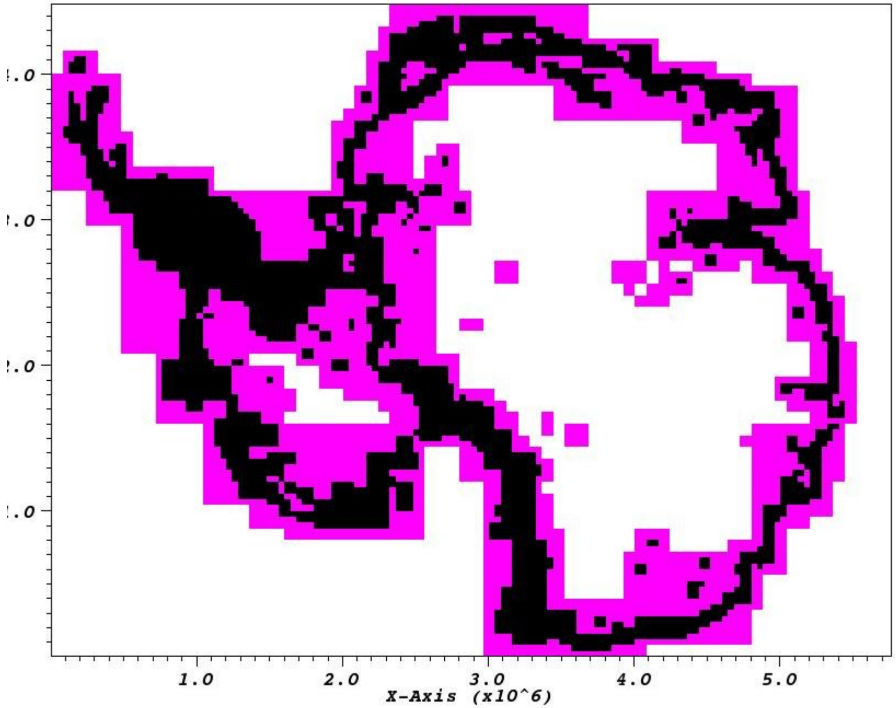




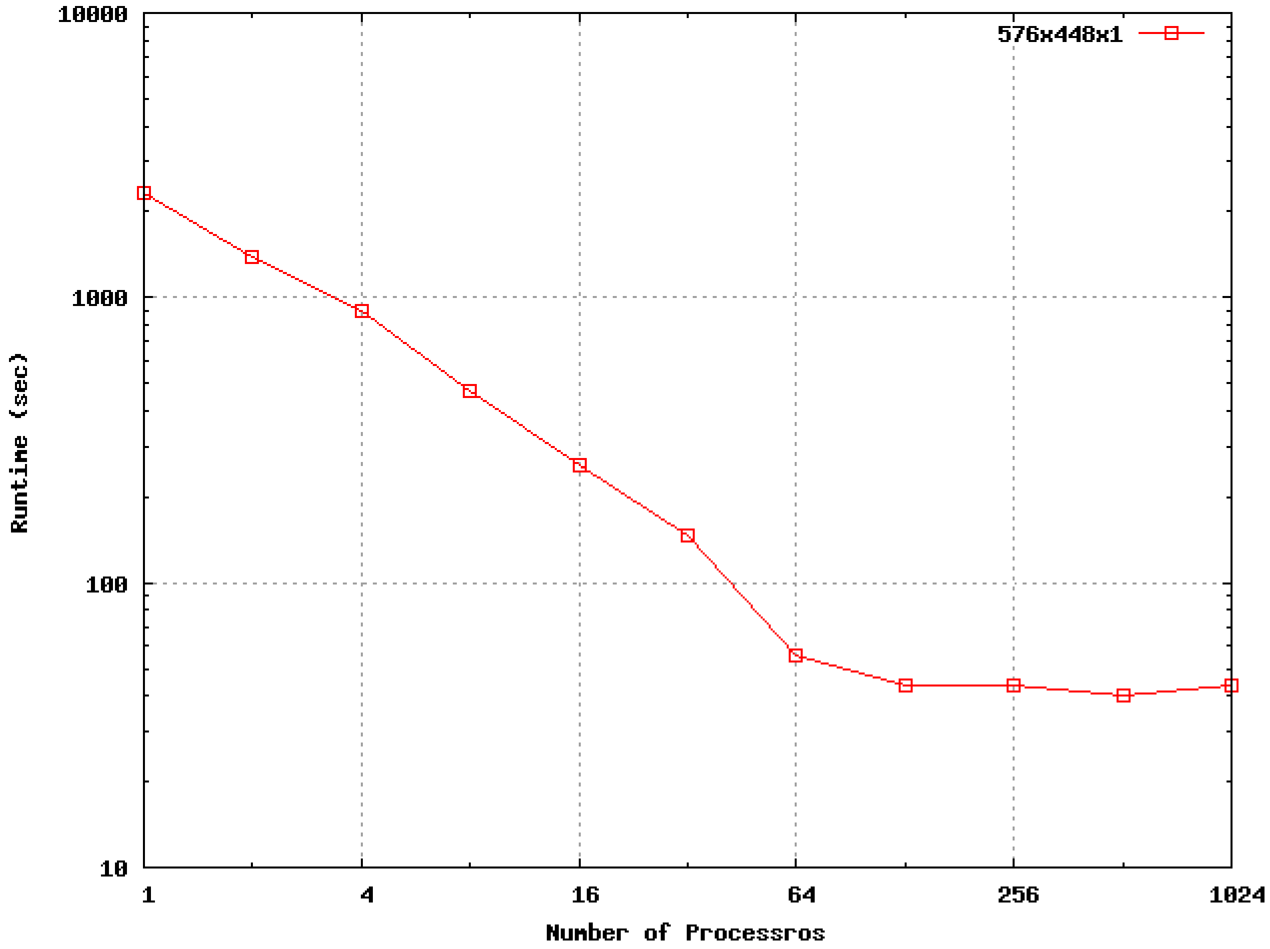
Antarctica, cont

- 10 km base mesh with 2 levels of refinement (5 km, 2.5 km)
  - base level (10 km): 258,048 cells (100% of domain)
  - level 1 (5 km): 431,360 zones (41.8% of domain)
  - Level 2 (2.5 km): 728,832 cells (17.7% of domain)





Parallel scaling, Antarctica benchmark



BISICLES – Next steps

- More work with linear and nonlinear velocity solves.
- Semi-implicit time-discretization for stability, accuracy.
- Finish coupling with existing Glimmer-CISM code and CESM
  - Testing with more complex and fully coupled problems
- Performance optimization and autotuning.
- Refinement in time?